Do Generation Firms in Restructured Electricity Markets Have Incentives to Support Socially-Efficient Transmission Investments? *

Enzo E. Sauma [a, **], Shmuel S. Oren [b]

[a] *Industrial and Systems Engineering Department, Pontificia Universidad Católica de Chile, Santiago, Chile*

[b] *Industrial Engineering and Operations Research Department, University of California, Berkeley, U.S.A.*

Abstract

This paper examines the incentives that generation firms have in restructured electricity markets for supporting long-term transmission investments. In particular, we study whether generation firms, which arguably play a dominant role in the restructured electricity markets, have the incentives to fund or support social-welfare-improving transmission investments. We examine this question and explore how such incentives are affected by the ownership of financial transmission rights (FTRs) by generation firms. We investigate the way in which the allocation of FTRs may be used to both align the incentives for supporting transmission expansions of the different market participants and mitigate conflicts of interest when such expansions are socially beneficial. Specifically, we show that if all FTRs were allocated or auctioned off to generation firms that are net exporters, then these firms would have the correct incentives to support social-welfare-improving transmission expansions. We illustrate these ideas in a simple two-node network.

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** Corresponding author. Address: Av. Vicuña Mackenna # 4860, Raúl Deves Hall, Piso 3, Macul, Santiago, Chile; tel.: 56 2 354 4272; fax: +56 2 552 1608; e-mail: esauma@ing.puc.cl.

1. Introduction

There is growing evidence that the U.S. transmission system is under stress (Abraham, 2002). Growth of electricity demand and new generation capacity, lack of investment in new transmission facilities, and the incomplete transition to efficient and competitive wholesale markets have allowed transmission bottlenecks to emerge. These bottlenecks increase consumer costs and reliability problems. That is, the increased use of the transmission grid has led to transmission congestion and less operating flexibility to respond to system problems or component failures. This lack of flexibility has increased the risk of power failures and blackouts. From an economic perspective, increased congestion reduces the ability to import power from remote cheap generators, thus raising the cost of energy. It also impedes trade and competition, which in turn makes consumers more vulnerable to the exercise of market power.

Construction of new transmission facilities and upgrades of existing facilities could alleviate transmission congestion and ensure future reliability of the U.S. electric system. Unfortunately, investment in new transmission facilities is lagging far behind both investment in new generation and growth in electricity demand.

Much of the current underinvestment in electricity transmission is a consequence of the poor incentive structures present in the U.S. system. Generation-unit owners profiting from congestion have no incentive to support transmission upgrades. Electricity retailers and regulated load serving entities, on the other hand, bundle congestion charges into their cost of purchasing wholesale electricity, which is passed on to consumers. Consumers, who could benefit from transmission upgrades, have little incentive to participate in the process due to free-rider effects. And transmission owners, who are expected to engage in transmission investments, receive a regulated rate of return, which is arguably insufficient to compensate them for the risk and cost of capital associated with such undertaking.

The so-called Standard Market Design (FERC, 2002), which prevails (or is in the process of being implemented) in the restructured electricity markets in the US, is "generation-centric". It relies on locational marginal prices for energy to price and manage congestion and to signal the need for economically driven transmission investments[1]. One of the basic problems, however, is that locational marginal prices have a short term nature and do not provide adequate incentives to motivate merchant investments in transmission, which are capital intensive and long term in nature. Studies addressing the insufficiency of incentives for investment in the U.S. electricity transmission system are sparse. Moreover, none of the incentive structures proposed in the literature have been broadly adopted.

Bushnell and Stoft (1996) apply the definition of financial transmission rights (rights that entitle holders to receive financial benefits derived from the use of the transmission capacity) in the context of nodal pricing systems. They suggest a transmission rights allocation rule based on the concept of feasible dispatch, and prove that such a rule can reduce or, under ideal circumstances, eliminate the incentives for a detrimental grid expansion while rewarding efficient investments.

Bushnell-and-Stoft's paper is based on the idea that transmission investors are granted financial rights (which are tradable among market participants) as a reward for the transmission capacity added to the network.[2] This scheme, in contrast with the actual rate-of-return-regulation regime, could provide, in principal, the correct incentive for new entrants to invest in new transmission capacity. The main idea in the Bushnell-and-Stoft paper is that a transmission investor is allowed to select any set of transmission rights which, when combined with the existing set, corresponds to a dispatch that is feasible under the constraints of the newly modified grid. An

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[1] Transmission investments are often driven by reliability considerations while the economic analysis serves for impact assessment and cost allocation.

[2] The concept of a decentralized allocation of financial transmission rights was originally developed by Hogan (1992), under the name of "contract network regime".

investor who creates an intentionally congested line, which effectively reduces the feasible set of dispatches, would, therefore, be required to accept a set of transmission rights and obligations that exactly cancel the flows that are no longer feasible in the resulting, lower capacity network. The concept of feasibility, thereby, provides some check on the incentive to create congestion.

Bushnell and Stoft (1996) show that, "under certain conditions", the mentioned simultaneous feasibility test can effectively deter detrimental investments. However, these conditions are very stringent. They assume that transmission investments are characterized by no-increasing returns to scale, there are no sunk costs, nodal prices reflect consumers' willingness to pay for electricity and reliability, all network externalities are internalized in nodal prices, transmission network constraints and associated point-to-point capacity are non-stochastic, there is no market power, markets are always cleared by prices, and the system operator has no discretion to affect the effective transmission capacity and nodal prices over time.

Joskow and Tirole (2003) reexamine the Bushnell-and-Stoft model after introducing assumptions that more accurately reflect the physical and economic attributes of real transmission networks. They show that a variety of potentially significant performance problems then arise. In particular, they claim that the Bushnell-and-Stoft definition of transmission rights does not adequately account for the stochastic and dynamic physical attributes of transmission networks. Consequently, they argue that property rights that are "contingent" on exogenous variations in transmission capacity and reflect the diversification attributes of new investments would be necessary to properly align investment incentives with the characteristics of transmission networks. Unfortunately, defining and allocating these contingent property rights is also likely to be inconsistent with the development of liquid competitive markets for these rights or derivatives on them.

In addition, Joskow and Tirole (2003) argue that the difficulty of "correctly" assigning financial transmission property rights is another deterrent to invest in the transmission system.

Under the Bushnell-and-Stoft's framework, the allocation of transmission property rights is made by an independent system operator (ISO) who looks for feasibility of the network using a sequence of simulations of the system. However, these types of assignments are arbitrary mainly because of the complexity of allocating network deepening investments (investments that involve upgrades of existing facilities).

The difficulty of correctly assigning financial transmission property rights is also addressed in Barmack et al. (2003). Differently from Joskow and Tirole (2003), they mention two other important reasons for the inefficiency of financial property rights with respect to incentives for transmission investment: (i) a transmission investment that eliminates congestion results in financial property rights that are worthless, and (ii) it may be difficult for transmission owners (TOs) to capture other benefit streams resulting from transmission investment.

Joskow and Tirole (2000) analyze how the allocation of transmission rights associated with the use of power networks affects the operational behavior of generation firms and consumers with market power. Their analysis, as well as the analysis in (Joskow and Tirole, 2003), focuses on an always-congested two-node network where there is a cheap generation monopolist in an exporting region that has no local demand and an expensive generation monopolist in an importing region that contains the entire-system demand. They conclude that if the generation firm in the importing region has market power, their holding financial transmission rights enhances that market power. In section 3.2 of this paper, we analyze the consequences of this finding on the incentives that generation firms have to support social-welfare-improving transmission expansions.

Several related studies try to improve the incentive structures for transmission investment by dealing with the generator's motivation to exercise market power. In (Cardell et al., 1997), (Joskow and Tirole, 2000), (Oren, 1997), and (Stoft, 1999), the authors study the implications of the exercise of market power in congested two- and/or three-node networks where the entire system demand is concentrated in only one node. The main idea behind these papers is that if an expensive generator with local market power is required to produce power as a result of network congestion, then the generation firm owning this generator may have a disincentive to relieve congestion. Borenstein et al. (2000) present an analysis of the relationship between transmission capacity and generation competition in the context of a two-node network in which there is local demand at each node. The authors argue that relatively small transmission investment may yield large payoffs in terms of increased competition. However, they only consider the case in which generation firms cannot hold transmission rights. In section 3.2 of this article, we extend this analysis to allow both local demand at each node of the network and the possibility that generation firms hold financial transmission rights.

The California Independent System Operator (CAISO) has recently developed a “Transmission Economic Assessment Methodology” (TEAM) for assessing transmission expansion projects, which is based on the *gains from trade* principle (Sheffrin, 2005), (CAISO, 2004). Although TEAM considers alternative generation-expansion scenarios with and without transmission upgrades, as far as we know, this generation-expansion analysis does not take into account the potential strategic response to transmission investment from generation firms who may alter their investment plans in new generation capacity. This rationale underlines common wisdom that prevailed in a regulated environment justifying the construction of transmission between cheap and expensive generation nodes on the grounds of reducing energy cost to consumers. However, as shown by Sauma and Oren (2006), such rationale may no longer hold in a market-based environment where market power is present.

Some other authors have proposed more radical changes to the transmission system. Barmack et al. (2003) propose the development of performance-based regulation (PBR) to operate the transmission network. Such a mechanism can be designed to align the interests of the TOs with the interests of society (i.e., PBR can be designed to induce the TOs to trade off congestion costs – or re-dispatch costs – on one hand, and the costs of investment in and operation of the grid on the other hand). Barmack et al. (2003) suggest that TOs collect a transmission fee subject to a price cap that is high enough to allow recovery of the expected operational and congestion costs. This PBR approach encourages TOs to reduce congestion costs while increasing their profits and the social surplus.

Oren, Gross and Alvarado (see (Oren et al., 2002) and (Alvarado and Oren, 2002)) propose a transmission model in which a for-profit independent transmission company (ITC) owns and operates most of its transmission resources and is responsible for operations, maintenance, and investment of the whole transmission system. This model has several advantages over the current U.S. transmission system:

- The ITC has no incentive to discriminate among generators.
- The ITC has the appropriate incentives to invest (because owning more transmission lines implies a decrease in the local market power of generation firms, a decrease in congestion costs, an increase in the trades realized, and an increase in the reliability of the system).
- This model allows TOs to capture other benefit streams.
- It does not have the problem of incorrect assignment of transmission rights.
- It has the appropriate incentives to maintain the availability of TO's lines.
- It has the correct incentives for assuming risk (since a reward-penalty mechanism is imposed).
- It could be socially efficient (if parameters are set correctly).

On the other hand, the ITC model has some disadvantages. Some of the shortcomings of the ITC model are:

- It constitutes a monopoly (this can be addressed by regulation through a PBR scheme).
- It could have a transmission bias (this is, a preference for a "wire solution" over a "generation solution" even if the latter is more cost-effective).
- It could have conflicts with regard to assets overlap or joint ownership with other regions.

- It must be created through divestiture of privately and publicly owned transmission assets.

The latter problem is probably the most difficult to solve in the U.S. because it requires legislative initiatives to empower Federal Energy Regulatory Commission (FERC) to both order divestiture of privately owned transmission assets and enable the divestiture of transmission assets owned by public power entities.

In view of the actual problem of underinvestment in transmission, FERC has recently proposed transmission pricing reforms designed to promote needed investment in energy infrastructure (FERC, 2005). Basically, FERC proposes an increase in the rate of return on equity (ROE), especially for stand-alone transmission companies (transcos), in order to both attract new investment in transmission facilities and encourage transco formation. This FERC proposal is based on the idea that incentives may be more effective in fostering new transmission investment for transcos than for traditional public utilities that are dependent upon retail regulators for some portion of their transmission cost recovery.

In this paper, we focus on the incentives that generation firms at generation pockets have to support transmission expansions and how these incentives are affected by the ownership of financial transmission rights (FTRs). We are interested in analyzing the effect of local market power on such incentives when considering both that generation firms can hold FTRs and that generation firms cannot hold FTRs. For simplicity, we will assume through this article that thermal transmission line capacities are static and deterministic.

The rest of the paper is organized as follows. Section 2 studies the distributional impacts of transmission investments. In section 3, we explore how FTRs allocation may be used to both align the incentives for transmission expansion of the different market participants and mitigate conflicts of interest when such expansions are socially beneficial, in the context of a two-node network. We illustrate the theoretical results obtained in section 3 through a numerical example presented in section 4. Section 5 concludes the paper.

2. Distributional Impacts of Transmission Investments

Before analyzing the transmission investment incentives of generation firms, it is worth to emphasize the well-known fact that transmission expansions generally have distributional impacts, which could potentially create conflicts of interests among the affected parties. The key issue is that, while society as a whole may benefit from the elimination of congestion, some parties may be adversely affected by a socially-beneficial investment.

In general, transmission investment effects rent transfers from load pocket generators and generation pocket consumers to load pocket consumers and generation pocket generators. However, load pocket consumers and generation pocket generators cannot simply decide to build a line linking them. Their decision will be subject to scrutiny by not only an ISO, but also state and federal energy and environmental regulators. In this type of environment, the “losers” from transmission investment can be expected to expend up to the amount of rents that they stand to lose to block the transmission investment. This rent dissipation is wasteful. Moreover, it may block socially-beneficial projects from being built. The following example illustrates the distributional impacts of transmission investments and the potential incentives that some market participants can have to exercise political power in order to block a socially-beneficial transmission expansion project.

Consider a network composed of two cities (nodes) satisfying their electricity demand with local generation firms. For simplicity, assume there exists only one (monopolist) generation firm in each city, which have unlimited generation capacity. We assume that the marginal cost of supply at city 1 is lower than that at city 2. In particular, suppose the marginal costs of generation are constant[3] and equal to \$10/MWh at city 1 and \$20/MWh at city 2. Assume the inverse demand functions are linear, given by $P_1(q_1) = 30 - 0.1 \cdot q_1$ at city 1 and by $P_2(q_2) = 60 - 0.1 \cdot q_2$ at city 2, in \$/MWh.

Under the monopolistic (self-sufficient-cities) scenario, the city 1 firm optimally produces $q_1^{(M)} = 100$ MWh (on an hourly basis) and charges a price $P_1^{(M)} = \$20$/MWh while the city 2 firm optimally produces $q_2^{(M)} = 200$ MWh and charges a price $P_2^{(M)} = \$40$/MWh. With these market-clearing quantities and prices, the firms' profits are $\Pi_1^{(M)} = \$1{,}000$/h and $\Pi_2^{(M)} = \$4{,}000$/h, respectively. The consumer surpluses are $CS_1^{(M)} = \$500$/h for city 1 consumers and $CS_2^{(M)} = \$2{,}000$/h for city 2 consumers.[4]

Now, consider the scenario in which there is adequate (ideally unlimited) transmission capacity between the two cities. This situation corresponds to a duopoly facing an aggregated demand given by (in \$/MWh):

$$P(Q) = \begin{cases} 60 - 0.1 \cdot Q & \text{, if } Q < 300 \\ 45 - 0.05 \cdot Q & \text{, if } Q \geq 300 \end{cases} \quad \text{, where } Q = q_1 + q_2.$$

We assume generation firms behave as Cournot oligopolists in this case. Under this situation, the firm at city 1 optimally produces $q_1^{(D)} = 300$ MWh (on an hourly basis) while the firm at city 2 optimally produces $q_2^{(D)} = 100$ MWh. The price charged by both firms is $P^{(D)} = \$25$/MWh. With these new market-clearing quantities and prices, the firms' profits are $\Pi_1^{(D)} = \$4{,}500$/h and $\Pi_2^{(D)} =$

[3] The assumption that marginal costs of supply are constant is not critical, but it simplifies the calculations.

[4] Under monopoly, a firm optimally chooses a quantity such that the marginal cost of supply equals its marginal revenue. If the marginal cost of production is constant and equal to c and the demand is linear, given by $P(q) = a - b \cdot q$, where $a > c$, then the monopolist will optimally produce $q^{(M)} = (a - c) / (2b)$ and charge a price $P^{(M)} = (a + c) / 2$, making a profit of $\Pi^{(M)} = (a - c)^2 / (4b)$. Under these assumptions, the consumer surplus is equal to $CS^{(M)} = (a - c)^2 / (8b)$.

\$500/h, respectively.[5] As well, the consumer surpluses are $CS_1^{(D)}$ = \$125/h for the city 1 consumers and $CS_2^{(D)}$ = \$6,125/h for the city 2 consumers.

In this example, by linking both cities through a high-capacity transmission line, we replace some expensive power produced at city 2 by cheaper power generated at city 1, which makes city 2 consumers better off. Unfortunately, this is not the only implication of the construction of such a transmission line. The presence of market power allow the city 1 firm to increase the electricity price (because of the higher demand observed by this firm after linking both cities), although its marginal cost of generation does not change at all. This fact makes the firm at city 1 better off and the city 1 consumers worse off with respect to the monopolistic scenario. Moreover, the city 2 firm reduces its profit because both its retail price and its production quantity decrease as result of the competition between generation firms introduced by the new transmission line.

Indeed, a quick observation of the numerical results reveals that the construction of the transmission line has the following consequences: the city 1-consumers' surplus decreases from \$500/h to \$125/h, the city 2-firm's profit decreases from \$4,000/h to \$500/h, the city 2-consumers' surplus increases from \$2,000/h to \$6,125/h, and the city 1-firm's profit increases from \$1,000/h to \$4,500/h. From these results, it is clear that the city 1 consumers (generation pocket consumers) and the city 2 firm (load pocket generator) will oppose the construction of the transmission line linking both cities because this line will decrease their surpluses, transferring their rents to the city 2 consumers (load pocket consumers) and the city 1 firm (generation pocket generator). Consequently, depending on the relative political power of the market participants, this network-

[5] Under duopoly, the Cournot firms simultaneously choose quantities such that their marginal cost of supply equals their marginal revenue, but assuming the quantity produced by the other firm is fixed. If the marginal costs of production are constant for both firms, given by c_1 and c_2 respectively, and the aggregate inverse demand is linear, given by $P(Q) = A - B \cdot Q$, where $A > c_1$ and $A > c_2$, then firm i will optimally produce $q_i^{(D)} = (A - 2c_i + c_j) / (3B)$, with $j \neq i$ and $i \in \{1,2\}$. Under these assumptions, the duopolistic price will be $P^{(D)} = (A + c_1 + c_2) / 3$ and firm i will make a profit of $\Pi_i^{(D)} = (A - 2c_i + c_j)^2 / (9B)$, with $j \neq i$ and $i \in \{1,2\}$.

expansion project could be blocked, even though it could be socially beneficial (depending on the transmission investment costs).

The problem of rent transfer may arise even in the absence of market power. To illustrate this fact, assume that city 1 (generation pocket) has 1,000 MW of local generation capacity at $10/MWh marginal cost and another 500 MW of generation capacity at $20/MWh marginal cost, with 600 MW of local demand, while city 2 has 800 MW of generation capacity at $30/MWh marginal cost and local demand of 1,000 MW. Furthermore, assume that all generation power is offered at marginal cost and that a 300 MW transmission line connects the two cities. Under this scenario, the market clearing prices are $10/MWh in city 1 and $30/MWh in city 2 and 300 MW are exported from city 1 to city 2. A 300 MW increase in transmission capacity would allow replacement of 300 MW of load served at $30/MWh by imports from city 1, of which 100 MW can be produced at $10/MWh and another 200 MW can be produced at $20/MWh. The social benefit from such an expansion is, therefore, $4,000/h. Assuming that the amortized upgrade costs is bellow $4,000/h the upgrade is socially beneficial. The market consequences of such an upgrade are that the market clearing price at city 1 increases from $10/MWh to $20/MWh while the market clearing price at city 2 stays $30/MWh as before, with 600 MW being exported from city 1 to city 2. Consequently, consumers and generators in city 2 are neutral to the expansion, consumer surplus in city 1 will drop by $6,000/h, generator's profits in city 1 will increase by $10,000/h, and the merchandising surplus of the system operator will remain unchanged (the ISO merchandising surplus on the pre-expansion imports drops $3,000/h, but it picks up $3,000/h for the incremental imports). Clearly, such an expansion is likely to face stiff opposition from consumer groups in city 1, but it would be strongly favored by the generators at city 1, who would be more than happy to pay for it (as long as the amortized investment cost does not exceed $10,000/h). In fact, generators at node 1 would favor such an investment even if its amortized cost exceed the

$4,000/h benefits, which would make such an investment socially inefficient to the detriment of city 1 consumers.

By contrast to the above example, a small incremental upgrade of 90 MW in the transmission capacity would be socially beneficial increasing social surplus by $1,800/h without affecting the market clearing prices in either city. In such a case, neither the generators nor the consumers on either side will benefit (or be harmed) by the expansion and, thus, the entire gain will go to the ISO in the form of merchandising surplus. In such a case, a merchant transmission owner could be induced to undertake the transmission upgrade in exchange for financial transmission rights (FTRs) that would entitle her to the locational marginal price differences for the incremental transmission capacity, thus allowing the investor to capture the entire social surplus gain due to the expansion.

In the following section, we will further explore how FTR allocation may be used to both align the incentives for transmission expansion of the different market participants and mitigate conflicts of interest when such expansions are socially beneficial.

3. Transmission Investment Incentives of Generation Firms

In analyzing the transmission investment incentives of generation firms, considering the implications of the exercise of local market power by generators becomes crucial. Here, we study this idea in the context of a radial, two-node network. This-section analysis shows that generation firms with local market power could have disincentives to support socially beneficial investments in a transmission network and that, if a generation firm with local market power holds FTRs, then these transmission rights could enhance its market power. However, our analysis also shows that if all FTRs were allocated to net exporter generation firms, then these firms would have the correct incentives to support incremental social-welfare-improving transmission expansions.

As general framework for the analysis presented in this section, we assume that the transmission system uses locational marginal pricing, generation firms behave as Cournot oligopolists, transmission losses are negligible, all transmission rights are financial rights (whose holders are rewarded based on congestion rents), and network investors are rewarded based on a regulated rate of return administered by a non-profit ISO, which manages transmission assets owned by many investors. The main two reasons for this choice are: (i) many of the U.S. transmission systems actually use this type of scheme and (ii) this structure has been proposed by FERC as part of its Standard Market Design (FERC, 2002).

We also assume that each market participant must trade power with an ISO, at the nodal price of its local node. Thus, the generation firm located at node i will receive a payment equal to the nodal price at node i times the quantity produced and the consumers at node j will pay an amount equal to the nodal price at node j times the quantity consumed.

Consider a network composed of two nodes linked by a transmission line of thermal capacity K. The non-depreciated capital and operating costs of the link are assumed to be recovered separately from consumers in lump-sum charges net of revenues produced by selling transmission rights and we do not consider these costs further in our analysis.

For simplicity, we assume that there is only one generation firm at each node, having unlimited generation capacity. We assume that the production cost functions of the two firms, say $C_1(q)$ and $C_2(q)$, are convex and twice differentiable in the firms' outputs (i.e., the firms' marginal costs of generation are continuously non-decreasing in the firms' outputs). We also assume that the inverse demand function at each node of the network, say $P_1(q)$ at node 1 and $P_2(q)$ at node 2, is continuous and downward sloping. Moreover, we suppose that, if the two markets were completely isolated (i.e., no connected by any transmission line), the generation firms would produce outputs q_1^M and q_2^M such that $P_1(q_1^M) < P_2(q_2^M)$. [6]

Let q_i (i = 1,2) be the quantity of energy produced by the generation firm located at node i, and let q_t be the net quantity exported from node 1 to node 2. This quantity (q_t) depends on both nodal prices and, thus, depends on both q_1 and q_2. Moreover, q_t must satisfy the transmission capacity constraints (i.e., it must satisfy $-K \le q_t \le K$, where a negative q_t represents a net flow from node 2 to node 1).

Our analysis considers two scenarios: first, a scenario in which generation firms cannot hold transmission rights and second, a scenario in which generation firms can hold FTRs.

3.1 Scenario I: generation firms cannot hold transmission rights

Assume generation firms cannot hold transmission rights (and, thus, their bidding strategy is independent of the congestion rent). Accordingly, in this case, the profit of the generation firm located at node 1 (cheapgen) is $\pi_1(q_1) = q_1 \cdot P_1(q_1 - q_t) - C_1(q_1)$ and the profit of the generation firm located at node 2 (deargen) is $\pi_2(q_2) = q_2 \cdot P_2(q_2 + q_t) - C_2(q_2)$.

When generation firms cannot hold transmission rights, showing that generation firms with local market power can have disincentives to support socially beneficial investments in the transmission system seems simple. We could argue that, by congesting the system,[7] generation firms have the ability to exercise their local market power and deliberately withhold their outputs (or equivalently, increase their nodal prices) so that they can increase their profits. However, we must be cautious in the analysis of the equilibrium conditions because nodal prices, $P_1(q_1 - q_t)$ and

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[6] This would be the case if, for example, both generation firms faced equal demand curves (i.e., $P_1(q) = P_2(q)$) and the marginal cost of supply at node 1 were lower than that at node 2 over the relevant range (i.e., $C_1'(q_1^M) < C_2'(q_2^M)$).

[7] In this section, the term “congestion” is used in the electrical engineering sense: a line is congested when the flow of power is equal to the line’s thermal capacity, as determined by various engineering standards.

$P_2(q_2 + q_t)$ in our example, are discontinuous at the point where the transmission line becomes congested (i.e., at $q_t = \pm K$).

In (Borenstein et al., 2000), the authors use a two-node network similar to the one described above. They showed that, as the thermal capacity of the transmission line, K, increases from zero, one of two possible outcomes is obtained: [8]

Case 1:

$0 < K < K'$	passive/aggressive (P/A) Nash equilibrium exists
$K' < K < K^*$	no pure-strategy Nash equilibrium exists
$K^* < K$	unconstrained Nash-Cournot equilibrium exists

or

Case 2:

$0 < K < K^*$	P/A Nash equilibrium exists
$K^* < K < K'$	both P/A and unconstrained Cournot Nash equilibria exists
$K' < K$	unconstrained Nash-Cournot equilibrium exists

where K' corresponds to the largest line capacity that can support a P/A Nash equilibrium (i.e., a pure-strategy Nash equilibrium in which the transmission line is congested with net flow from the lower-price – under monopoly – market to the higher-price market) and K* represents the smallest transmission line capacity that can support an unconstrained Nash-Cournot duopoly equilibrium (i.e., a Nash-Cournot duopoly equilibrium in which K is high enough so that the line is never congested).

One can derive the best-response (in quantity) functions of each firm for each one of the two previous cases. Figure 1, reproduced from (Borenstein et al., 2000), illustrates the best-response functions in case 2 (i.e., the overlapping equilibria case).

[8] See Theorem 5 in (Borenstein et al., 2000).

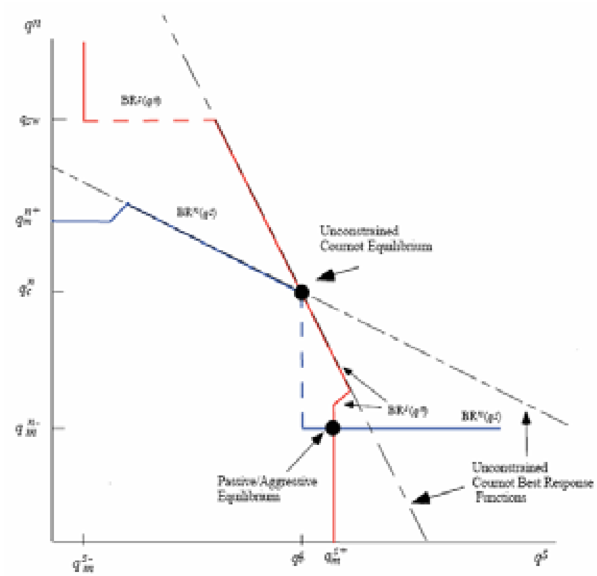

Figure 1: Best-response functions in the overlapping equilibria case.

Reproduced from Figure 7 in (Borenstein et al., 2000).

Accordingly, if the transmission line capacity is high enough (i.e., K > Max{K', K*}), then an unconstrained Nash-Cournot duopoly equilibrium exists and it corresponds to the unique pure-strategy Nash equilibrium. In this case, there is no congestion at the Nash equilibrium and q_t is far enough from ± K so that both $P_1(q_1 - q_t)$ and $P_2(q_2 + q_t)$ are continuous and differentiable over the relevant range. Thus, the unconstrained Nash-Cournot duopoly equilibrium (in which each firm maximizes its profit taking the output of the other firm as fixed subject to the fact that nodal prices must be equal at both nodes) is characterized by the following system of equations (first order optimality conditions):

$$P_1(q_1 - q_t) + q_1 \cdot \frac{d\left(P_1(q_1 - q_t)\right)}{dq_1} = C_1'(q_1), \tag{1}$$

$$P_2(q_2 + q_t) + q_2 \cdot \frac{d\left(P_2(q_2 + q_t)\right)}{dq_2} = C_2'(q_2), \tag{2}$$

$$P_1(q_1 - q_t) = P_2(q_2 + q_t), \tag{3}$$

$$-K < q_t < K, \tag{4}$$

$$q_1, q_2 \geq 0 \tag{5}$$

These optimality conditions are only valid under the assumption that, at the equilibrium, q_t is far enough from ± K. The only way to guarantee this fact is by ensuring that the transmission line capacity is high enough so that the line is never congested. However, this is not an interesting case to analyze from the point of view of the transmission investment incentives because generation firms have obviously no incentives to support an increment in the capacity of a line that has large excess capacity.

On the other hand, if the transmission line capacity is low enough (i.e., K < Min{K', K*}), then generation firms maximize their profits by acting according to a Nash equilibrium in which the transmission line is congested with net flow from the lower-price (under monopoly) market to the higher-price market (i.e., a P/A Nash equilibrium). In this case, $q_t = K$ (i.e., the line is congested with net flow from node 1 to node 2) and the discontinuity of both $P_1(q_1 - q_t)$ and $P_2(q_2 + q_t)$ at the point where the line is congested becomes problematic (i.e., as q_t approach to K, $d(P_1(q_1 - q_t))/dq_1$ and $d(P_2(q_2 + q_t))/dq_2$ are not well defined). Thus, we must check the equilibrium conditions without using derivatives.

Consider a P/A point of operation, (q_1^c, q_2^c), that maximizes the firms' profits given that the quantity exported from node 1 to node 2 is fixed and equal to the line capacity (i.e., subject to the fact that the line is congested with flow from node 1 to node 2). That is, q_1^c is the profit-maximizing output of the cheapgen when it faces an inverse demand curve given by $P_1(q_1 - K)$, which is the cheapgen's native inverse demand shifted rightward by K, and q_2^c is the output of the deargen when it maximizes its profit given the residual inverse demand it faces, $P_2(q_2 + K)$, which is the deargen's native inverse demand shifted leftward by K. In this case, the cheapgen effectively acts as a monopolist on the rightward-shifted inverse demand curve and the deargen effectively acts as a monopolist on its residual inverse demand curve. Borenstein et al. (2000) show that, for sufficiently small transmission capacity, the quantities (q_1^c, q_2^c) are the unique pure-strategy Nash equilibrium. [9] Although the proof presented in (Borenstein et al., 2000) correctly analyzes the incentives that the generation firms have to not deviate from the equilibrium, the fact that both $P_1(q_1–q_t)$ and $P_2(q_2+q_t)$ are discontinuous at the point where the line is congested and the associated complexities are not explicitly addressed in the proof. In the appendix, we offer an alternative proof that (q_1^c, q_2^c) is a pure-strategy Nash equilibrium, taking care of all the details about discontinuities. Table 1 summarizes the rationale of this proof.

Table 1: Rationale of proof that (q_1^c, q_2^c) is a Nash equilibrium.

FIRM	DEVIATION	POSSIBLE SCENARIOS	CONSEQUENCE
Cheapgen	Decrease output $q_1^c \rightarrow q_1^c - \varepsilon$ ($\varepsilon > 0$)	(i) q_t unchanged and ($q_1^c–q_t$) decreases by ε	Line still congested, $P_1(q_1^c–q_t)$ increases, ($q_1^c–q_t$) decreases ⇒ π_1 decreases.
		(ii) q_t decreases by ε and ($q_1^c–q_t$) unchanged	Line decongested ⇒ it is optimal to congest the line again.
		(iii) both q_t and ($q_1^c–q_t$) decrease by less than ε.	Line decongested, π_1 decreases ⇒ it is optimal to congest the line again.
Cheapgen	Increase output $q_1^c \rightarrow q_1^c + \varepsilon$ ($\varepsilon > 0$)	(i) q_t unchanged and ($q_1^c–q_t$) increases	Line still congested, $P_1(q_1^c –q_t)$ decreases, ($q_1^c–q_t$) increases ⇒ π_1 decreases.
		(ii) q_t decreases and ($q_1^c–q_t$) increases	Line decongested, $P_1(q_1^c –q_t)$ decreases ⇒ it is optimal to congest the line again.
Deargen	Increase output $q_2^c \rightarrow q_2^c + \varepsilon$ ($\varepsilon > 0$)	(i) q_t unchanged and ($q_2^c+q_t$) increases by ε	Line still congested, $P_2(q_2^c+q_t)$ decreases, ($q_2^c+q_t$) increases ⇒ π_2 decreases.
		(ii) q_t decreases by ε and ($q_2^c+q_t$) unchanged	Line decongested ⇒ it is optimal to allow a congested line again.
		(iii) q_t decreases by less than ε and ($q_2^c+q_t$) increases	Line decongested, π_2 decreases ⇒ it is optimal to allow a congested line again.

[9] See Theorem 4 in (Borenstein et al., 2000).

Deargen	Decrease output $q_2^c \rightarrow q_2^c - \varepsilon$ ($\varepsilon > 0$)	(i) q_t unchanged and $(q_2^c+q_t)$ decreases	Line still congested, $P_2(q_2^c+q_t)$ increases, $(q_2^c+q_t)$ decreases $\Rightarrow \pi_2$ decreases.
		(ii) both q_t and $(q_2^c+q_t)$ decrease	Line decongested, $P_2(q_2^c+q_t)$ increases $\Rightarrow$ it is optimal to allow a congested line again.

Now, we analyze the incentives/disincentives that the generation firms have to support an increase in the capacity of the transmission line while the Nash equilibrium characterized by (q_1^c, q_2^c) prevails. Suppose the thermal capacity of the transmission line is increased by a small positive amount, ΔK, such that the P/A Nash equilibrium is still supported. Then, the cheapgen will act as a monopolist on the (K+ΔK)-rightward-shifted inverse demand curve and, consequently, it will reoptimize its profit by increasing its output so that q_t is augmented by ΔK (i.e., congest the line again). Accordingly, the cheapgen's new optimal output, $q_1^{c\,(K+\Delta K)}$, will be larger than q_1^c and the new optimal price at node 1, $P_1(q_1^{c\,(K+\Delta K)} - (K+\Delta K))$, will be greater or equal to that before the expansion (because the consumption at node 1 must either decrease or remain equal at the new optimum).[10] Therefore, the cheapgen will definitely have positive incentives to support this transmission expansion because it increases the cheapgen's profit. Figure 2 illustrates this situation.

[10] When the thermal capacity of the transmission line increases by ΔK, the cheapgen could increase its output in ΔK and keep the same retail price at node 1 (making node 1 consumers indifferent and node 2 consumers better off), obtaining an extra profit equal to $\Delta K \cdot P_1(q_1^c - K)$. However, the fact that the cheapgen now faces a higher demand motivates it to exercise its local market power, reducing its output from the theoretical $q_1^c + \Delta K$ (while, of course, still resulting in an output greater than q_1^c) in order to increase the price at node 1 and, thus, increase its profit. That is, the cheapgen will now act as a monopolist on the (K+ΔK)-rightward-shifted inverse demand curve and reoptimize its profit by increasing its output in such a way so that the line is congested and the profit gained due to the nodal price increase, $q_1^{c(K+\Delta K)} \cdot (P_1(q_1^{c(K+\Delta K)} - (K+\Delta K)) - P_1(q_1^c - K))$, is larger than the profit "lost" due to the fact that the output is increased by less than ΔK, $(q_1^c + \Delta K - q_1^{c(K+\Delta K)}) \cdot P_1(q_1^c - K)$. Figure 2 illustrates these facts.

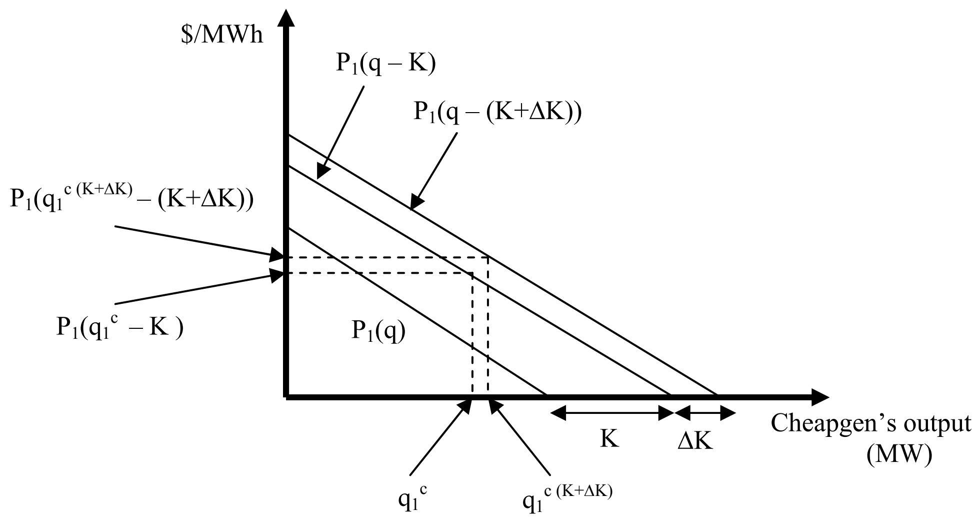

Figure 2: Transmission investment incentives of the cheapgen in the considered two-node network

On the other hand, when the line capacity is increased by this small positive amount, ΔK, the deargen's best response is to produce its optimal "passive" output. That is, the deargen will act as a monopolist on its residual, (K+ΔK)-leftward-shifted, inverse demand curve and reoptimize its profit by decreasing its output. The new optimal output, $q_2^{c(K+\Delta K)}$, will be smaller than q_2^c and the new optimal price at node 2, $P_2(q_2^{c\ (K+\Delta K)} + (K+\Delta K))$, will be smaller or equal than before the expansion (because the consumption at node 2 must either increase or remain equal at the new optimum).[11] Therefore, the deargen will have disincentives to support this transmission expansion because it decreases the deargen's profit. Figure 3 illustrates this situation.

[11] If the deargen kept its output at the q_2^c level even after increasing the thermal capacity of the line by ΔK, the price at node 2 would decrease from $P_2(q_2^c+K)$ to $P_2(q_2^c+K+\Delta K)$, producing a lost in the deargen profit (with respect to the pre-expansion situation) equal to $q_2^c \cdot (P_2(q_2^c+K) - P_2(q_2^c+K+\Delta K))$. However, the deargen could exercise its local market power and reduce its output in order to increase the price at node 2 with respect to the theoretical price $P_2(q_2^c+K+\Delta K)$ and, thus, increase its profit with respect to the situation in which the deargen keeps the output at the q_2^c level. That is, the deargen will now act as a monopolist on the (K+ΔK)-leftward-shifted inverse demand curve and reoptimize its profit by reducing its output in such a way so that the line is congested and the "gain" in profit, $q_2^{c(K+\Delta K)} \cdot (P_2(q_2^{c(K+\Delta K)}+K+\Delta K) - P_2(q_2^c+K+\Delta K))$, is larger than

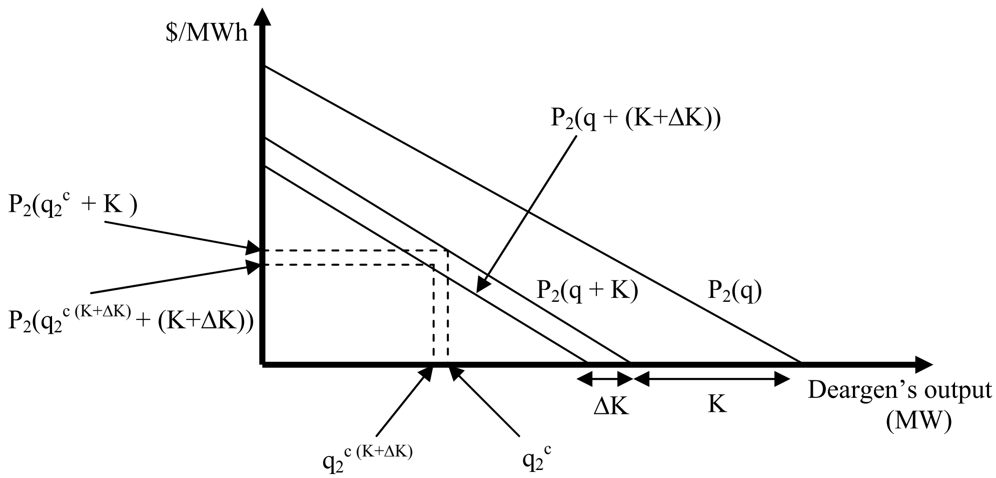

Figure 3: Transmission investment incentives of the deargen in the considered two-node network.

Therefore, when the equilibrium characterized by (q_1^c, q_2^c) is accomplished, the cheapgen has incentives to support an increase in the capacity of the transmission line by some small positive amount (such that the P/A Nash equilibrium is still supported) while the deargen has disincentives to support such a transmission expansion. However, this analysis is only valid for small incremental expansions of the line. As the size of the line upgrade increases, the P/A Nash equilibrium may no longer be supported (i.e., the best response of the deargen could be to increase significantly its output so that it either decongests the line or congests the line with net flow in the opposite direction). If this occurred, then it is unclear whether the cheapgen would still have incentives to support the expansion of the transmission line.

In fact, if the network upgrade were large enough so that it led to an unconstrained Nash-Cournot duopoly equilibrium, then such an investment would likely reduce the profits of both

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the lost in profit, $(q_2^c - q_2^{c(K+\Delta K)}) \cdot P_2(q_2^c+K+\Delta K)$, due to the reduction in the output with respect to the hypothetical case that the deargen keeps the output at q_2^c. Figure 3 illustrates these facts.

generators.[12] Moreover, because transmission investments tend to be lumpy, most transmission investments are likely to be large enough so that if they took place, then they would relieve all the congestion on the link (i.e., they would lead to an unconstrained Nash-Cournot duopoly equilibrium in the case of our two-node network example). Consequently, in most of the cases where the two markets have similar size and similar generation costs, neither the cheapgen nor the deargen have incentives to support such transmission expansions (although they could improve social welfare) because such expansions would reduce their profits. These results are illustrated through a simple numerical example, presented in section 4.1, where demand functions are linear and generation firms have constant marginal costs.

A remaining question in our analysis is what happens with the generation firms' incentives to support social-welfare-improving transmission expansions when the line capacity is neither too small nor too high (i.e., when K is such that $Min\{K',K^*\} < K < Max\{K',K^*\}$). Such analysis is very complex because the existence of a pure-strategy Nash equilibrium is not guaranteed in this case. Although we leave this analysis as future work, our intuition is that, even under mixed-strategy Nash-Cournot equilibria, expected nodal prices will decline as the line capacity increases. With a very thin transmission line, for instance, nodal prices should be very close to the monopoly levels. If they were not, then either firm could improve its expected profit by simply admitting imports of K and producing the optimal passive output as a pure strategy. With K near K*, the lower bounds on prices provided by the optimal passive output responses should be much weaker and the mixed strategy would be more likely to result in lower expected prices.

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[12] If the two markets are comparable and the two firms have similar generation costs, then we obtain the well-known result that a large enough investment that "moves" the pure-strategy Nash equilibrium from a P/A Nash equilibrium to an unconstrained Nash-Cournot duopoly equilibrium reduces the profits of both generators because nodal prices "discontinuously jump down" (although firms' outputs increase).

3.2 Scenario II: generation firms can hold FTRs

Assume now that generation firms can hold some FTRs. In particular, suppose that the cheapgen and the deargen hold fractions α_1 and α_2 of the K FTRs available from node 1 to node 2, respectively. These fractions must satisfy $\alpha_1 + \alpha_2 \leq 1$, where α_1 and $\alpha_2 \in [0,1]$. Thus, in our two-node network, the cheapgen now maximizes the following profit function (making rational expectations of the deargen's outcome):

$$\pi_1(q_1, \alpha_1) = q_1 \cdot P_1(q_1 - q_t) - C_1(q_1) + \alpha_1 \cdot K \cdot [\ P_2(q_2 + q_t) - P_1(q_1 - q_t)\ ] \qquad (6)$$

Likewise, the deargen now maximizes the following profit function (making rational expectations of the cheapgen's outcome):

$$\pi_2(q_2, \alpha_2) = q_2 \cdot P_2(q_2 + q_t) - C_2(q_2) + \alpha_2 \cdot K \cdot [\ P_2(q_2 + q_t) - P_1(q_1 - q_t)\ ] \qquad (7)$$

Generation firms must acquire their FTRs through some type of allocation scheme or auction. However, such an allocation scheme or auction has a relatively long time horizon as compared to the spot energy market. Hence we will treat any expenditure for acquiring FTRs as sunk cost, assuming generation firms only optimize their short-term profit functions.

If the transmission line capacity were high enough (i.e., $K > \text{Max}\{K', K^*\}$)[13] so that an unconstrained Nash-Cournot duopoly equilibrium would exist (and it would correspond to the unique pure-strategy Nash equilibrium), then there would be no congestion at the equilibrium. This means that the nodal prices at both ends of the uncongested line would be equal. Accordingly, all FTRs would become worthless due to the zero nodal price difference. Consequently, when the transmission line capacity is high enough, so that there is no congestion at the Nash equilibrium, the fact that generation firms can hold FTRs does not make any difference in profits as compared to the benchmark case (without FTRs). Thus, in this case, the unconstrained

[13] Here, we maintain the same notation as in the case without FTRs. That is, K' corresponds to the largest line capacity that can support a P/A Nash equilibrium and K* represents the smallest line capacity that can support an unconstrained Nash-Cournot duopoly equilibrium.

Nash-Cournot duopoly equilibrium is characterized by the same system of equations (first order optimality conditions) as in the benchmark case, i.e. equations (1) to (5). As we mentioned in the case without FTRs, this is not an interesting case to analyze from the point of view of the transmission investment incentives because generation firms have obviously no incentives to support an increment in the capacity of a line that has excess capacity.

On the other hand, if the transmission line capacity were low enough (i.e., $K < \text{Min}\{K', K^*\}$) so that a P/A Nash equilibrium were supported, then the transmission line would be congested with net flow from node 1 to node 2 (i.e., $q_t = K$) at the unique pure-strategy Nash equilibrium. The proof that the outcome $(q_1^c(\overline{\alpha_1}),\ q_2^c(\overline{\alpha_2}))$, which maximizes the generation firms' profits given both that the line is congested with flow from node 1 to node 2 and that α_1 and α_2 have fixed values ($\overline{\alpha_1}$ and $\overline{\alpha_2}$, respectively), is a Nash equilibrium is analogous to the case without FTRs and, thus, it will be omitted.

When the P/A Nash equilibrium is supported, the cheapgen maximizes its profit as if it had monopoly power over its K-rightward-shifted inverse demand function, but having two revenues streams now: a first stream of revenue from sales of energy and a second stream of revenues from the congestion rents from the FTRs. As the fraction of FTRs that the cheapgen holds increases, the cheapgen is more likely to sacrifice some profits it would otherwise earn from supplying energy in order to increase the profits it receives in the form of dividends on the FTRs it holds. Accordingly, while the P/A Nash equilibrium is supported, the larger α_1, the stronger the cheapgen's incentive to increase its production and, in this way, decrease the price at node 1. This fact becomes clear when we rewrite (6) as in (8) (considering, in addition, that the cheapgen both maximizes its profit and faces a downward-sloping inverse demand function).

$$\begin{aligned}\pi_1(q_1, \alpha_1) &= q_1 \cdot P_1(q_1 - q_t) - C_1(q_1) + \alpha_1 \cdot K \cdot [\, P_2(q_2 + q_t) - P_1(q_1 - q_t)\,] \\ &= (q_1 - \alpha_1 \cdot K) \cdot P_1(q_1 - q_t) - C_1(q_1) + \alpha_1 \cdot K \cdot P_2(q_2 + q_t) \qquad (8)\end{aligned}$$

Consequently, while the P/A Nash equilibrium prevails, the cheapgen effectively increases the price elasticity of its residual demand curve by holding FTRs.[14]

On the other hand, when the P/A Nash equilibrium is supported, the deargen maximizes its profit as if it had monopoly power over its K-leftward-shifted inverse demand function, but having two revenues streams now: a first stream of revenue from energy sales and a second revenue stream from the congestion rents. As the fraction of FTRs that the deargen holds increases, the deargen is more likely to sacrifice some profits it would otherwise earn from supplying energy in order to increase the profits it receives in the form of dividends on the FTRs it holds. Accordingly, while the P/A Nash equilibrium prevails, the larger α_2, the stronger the deargen's incentives to decrease its production and, in this way, increase the price at node 2. This statement becomes evident when we rewrite (7) as in (9) (considering, in addition, that the deargen both maximizes its profit and faces a downward-sloping inverse demand function).

$$\begin{aligned}\pi_2(q_2, \alpha_2) &= q_2 \cdot P_2(q_2 + q_t) - C_2(q_2) + \alpha_2 \cdot K \cdot [\, P_2(q_2 + q_t) - P_1(q_1 - q_t)\,] \\ &= (q_2 + \alpha_2 \cdot K) \cdot P_2(q_2 + q_t) - C_2(q_2) - \alpha_2 \cdot K \cdot P_1(q_1 - q_t) \qquad (9)\end{aligned}$$

Consequently, while the P/A Nash equilibrium prevails, the deargen effectively reduces the price elasticity of its residual demand curve and increases its local market power by holding FTRs.

The previous analysis leads to the conclusion that the optimal cheapgen's output, $q_1(\alpha_1)$, is increasing continuously in α_1, from $q_1(0)$ (benchmark case) to $q_1(1)$, while the optimal deargen's output, $q_2(\alpha_2)$, is decreasing continuously in α_2, from $q_2(0)$ (benchmark case) to $q_2(1)$. Again, this monotonicity is based on the rationale that, with FTR holdings, generation firms have two revenue streams: a first stream of revenue from sales of energy and a second stream of revenues from the congestion rents from the FTRs. The more generation firms internalize the congestion rents, the

[14] When holding FTRs, the cheapgen has incentive to increase its output and, consequently, decrease its nodal price. This is translated into an incentive to increase the elasticity of demand, $\varepsilon(q)$, because $\varepsilon(q) \approx \frac{dq}{dp} \cdot \frac{p}{q} = \frac{p}{q \cdot P'(q)}$ where P'(q) < 0.

higher the congestion rents are due to the firms' ability to influence nodal prices. Consequently, as α_1 increases, the cheapgen has stronger incentive to increase its production (and, in this way, to decrease the price at node 1) in order to increase its profit from congestion rents. Therefore, as the cheapgen holds more FTRs, the consumers located at node 1 benefit more from the resulting nodal price reduction. This fact could justify the allocation of all FTRs to net exporter generation firms (the cheapgen, in our two-node network) because this could increase social welfare.[15] In section 4.2, we illustrate the above theoretical results using a numerical example (the same numerical example we employ under the benchmark scenario).

Additionally, as in the benchmark scenario, it is easy to prove that, for fixed values of α_1 and α_2, and while the P/A Nash equilibrium prevails, the cheapgen has incentives to support an increase in the capacity of the transmission line while the deargen has disincentives to support such a transmission expansion. As mentioned before, this conclusion is only valid for sufficiently small transmission upgrades such that the transmission line capacity does not exceed K'. However, under this second scenario, both generation firms will support a P/A Nash equilibrium up to a line capacity larger than the benchmark case threshold. That is, the value of K' increases as α_1 and/or α_2 increase. Consequently, while the P/A Nash equilibrium prevails, it is more likely that the cheapgen supports a social-welfare-improving transmission expansion when it holds FTRs than when it does not hold FTRs.

4. Numerical Example

In this section, we use a numerical example to illustrate the previous-section findings about the incentives that generation firms have to support social-welfare-improving transmission expansions under both scenarios: with and without FTRs.

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[15] This conclusion is valid under our assumption that each market participant must trade with the ISO at the nodal price of its local node or trade bilaterally, paying congestion rents based on nodal price differences.

Under both scenarios, we assume that the inverse demand functions are $P_1(q) = 100 - 0.1 \cdot q$ at node 1 and $P_2(q) = 120 - 0.2 \cdot q$ at node 2 (in \$/MWh) and that the marginal costs of generation are zero for the cheapgen and \$20/MWh for the deargen. We also assume that there exists a transmission line connecting both nodes.

4.1 Scenario I: generation firms cannot hold transmission rights

If the thermal capacity of the line linking both nodes were very high, then the transmission capacity constraint would not be binding and the firms would compete as Cournot duopolists in the combined market. In such a case, at the unique pure-strategy Nash equilibrium, the cheapgen would hourly produce 633 MWh while the deargen would hourly generate 333 MWh and the market-clearing price would be \$42.2/MWh at both nodes. Thus, with such a high-capacity line, the cheapgen would earn a profit of \$26,741/h and the deargen would earn a profit of \$7,407/h. Under these conditions, and without considering any investment cost, social welfare would be \$65,963/h.

The smallest transmission line capacity that can support an unconstrained Nash-Cournot duopoly equilibrium, K*, is approximately equal to 115 MW in this numerical example. We computed K* as follows.

The deargen's profit, when a line of capacity K is congested into its market, is given by $\pi_2(q_2^c) = q_2^c \cdot P_2(q_2^c+K) - C_2(q_2^c) = q_2^c \cdot [120 - 0.2 \cdot (q_2^c+K)] - 20 \cdot q_2^c = (100 - 0.2 \cdot K) \cdot q_2^c - 0.2 \cdot (q_2^c)^2$, and the first order optimality condition of the deargen's profit maximization problem implies that $q_2^{c*} = 2.5 \cdot (100 - 0.2 \cdot K)$, where q_2^{c*} is the deargen's optimal passive output. Thus, the deargen's profit from producing its optimal passive output is: $\pi_2(q_2^{c*}) = (100 - 0.2 \cdot K) \cdot q_2^{c*} - 0.2 \cdot (q_2^{c*})^2 = 0.05 \cdot (500 - K)^2$. Consequently, the line capacity that makes the deargen indifferent between producing its unconstrained Nash-Cournot duopoly equilibrium output, q_2^{UCDE}, and producing its optimal passive output, q_2^{c*}, given that the cheapgen is producing its unconstrained Nash-Cournot duopoly equilibrium output, must satisfy the condition $\pi_2(q_2^{UCDE}) = \pi_2(q_2^{c}*)$, or equivalently, $7{,}407 = 0.05\cdot(500 - K^*)^2$. Thus, $K^* = 500 - \sqrt{(7{,}407 / 0.05)} \approx 115$ MW. □

With K = K* (≈ 115 MW), the deargen is indifferent between producing its unconstrained Nash-Cournot equilibrium hourly output (i.e., 333 MWh) and producing its optimal passive response (i.e., 193 MWh), given that the cheapgen is producing 633 MWh (i.e., its unconstrained Nash-Cournot equilibrium hourly output). At any larger K, each generation firm would strictly prefer the unconstrained Nash-Cournot duopoly equilibrium outcome to its optimal passive output response when the other firm produces its unconstrained Nash-Cournot equilibrium quantity.

For a transmission line of capacity slightly less than K*, K = 110 MW for instance, the unconstrained Nash-Cournot equilibrium is not attainable; the deargen would (just barely) prefer to produce the optimal passive output than play its Cournot best response to the cheapgen producing its unconstrained Nash-Cournot equilibrium quantity. But if the deargen produced its optimal passive output (i.e., 195 MWh), then the cheapgen would revert to sell its profit-maximizing quantity that congest the transmission line (i.e., 555 MWh). This amount is smaller than the cheapgen's Nash-Cournot equilibrium quantity (i.e., 633 MWh). As the cheapgen reduces its output, producing its optimal passive output becomes less attractive to the deargen. If that were the case, then the deargen would jump to produce its Cournot best response to 555 MWh, which is 373 MWh. With the line uncongested, however, the cheapgen would then respond with its Cournot best response of 614 MWh, and the process would once again iterate toward the unconstrained Nash-Cournot equilibrium. However, because the line capacity is just slightly below the level that can support the unconstrained Nash-Cournot equilibrium, as the cheapgen's output approaches its Nash-Cournot equilibrium quantity (i.e., 633 MWh), and strictly before it equals that quantity, the deargen will once again revert to produce its optimal passive output. Consequently, no pure-strategy Nash equilibrium exists in this case. The situation described in this paragraph will occur for any line capacity between K' and K*.

The largest line capacity that can support a P/A Nash equilibrium, K', is approximately equal to 53.6 MW in this numerical example. To compute K', we proceed as follows.

The cheapgen's profit, when a line of capacity K is congested from its market, is given by $\pi_1(q_1^c) = q_1^c \cdot P_1(q_1^c - K) - C_1(q_1^c) = q_1^c \cdot[100 - 0.1\cdot(q_1^c - K)] - 0 = (100 + 0.1\cdot K)\cdot q_1^c - 0.1\cdot(q_1^c)^2$, and the first order optimality condition of the cheapgen's profit maximization problem implies that $q_1^{c*} = 5\cdot(100 + 0.1\cdot K)$, where q_1^{c*} is the cheapgen's optimal aggressive output. Thus, the deargen's Cournot best response to q_1^{c*} is a quantity $q_2^{c(BR)}$ satisfying:

$$q_2^{c(BR)} = \text{Argmax}_{\{q_2\}} \; \overline{\pi_2}(q_2) \; ,$$

where $\overline{\pi_2}(q_2) = q_2 \cdot P(q_1^{c*} + q_2) - C_2(q_2) =$

$$= q_2 \cdot [106.67 - 0.067 \cdot (q_1^{c*} + q_2)] - 20\cdot q_2 =$$

$$= q_2\cdot [106.67 - 0.067 \cdot (5\cdot(100 + 0.1\cdot K) + q_2)] - 20\cdot q_2 =$$

$$= (53.3 - 0.033\cdot K)\cdot q_2 - 0.067\cdot(q_2)^2.$$

The first-order optimality condition implies that $q_2^{c(BR)} = 0.25\cdot(1600 - K)$. Thus, the deargen's profit from producing the Cournot best response to q_1^{c*} is:

$$\overline{\pi_2}(q_2^{c(BR)}) = (53.3 - 0.033\cdot K)\cdot q_2^{c(BR)} - 0.067\cdot(q_2^{c(BR)})^2 = (1600 - K)^2 / 240.$$

Consequently, the line capacity that leaves the deargen indifferent between producing its Cournot best response to the cheapgen's aggressive output (i.e., $q_2^{c(BR)}$) and producing its optimal passive output (i.e., q_2^{c*}) must satisfy $\overline{\pi_2}(q_2^{c(BR)}) = \pi_2(q_2^{c*})$. Recalling that the deargen's profit when producing its optimal passive response to q_1^{c*} is $\pi_2(q_2^{c*}) = 0.05\cdot(500 - K)^2$, we conclude that K' must satisfy the following equality: $(1600 - K')^2 / 240 = 0.05\cdot(500 - K')^2$. Thus, we have

$$K' = \frac{500 * \sqrt{12} - 1{,}600}{\sqrt{12} - 1} \approx 53.6 \text{ MW} . \; \square$$

With K = K’ (≈ 53.6 MW), the deargen is indifferent between producing its Cournot best response to the cheapgen’s aggressive output and producing its optimal passive output. At any smaller K, each generation firm would strictly prefer the P/A Nash equilibrium outcome to its Cournot best response when the other firm produces its P/A Nash equilibrium quantity.

Summarizing, for a transmission line of thermal capacity smaller than 53.6 MW (i.e., for K such that 0 < K < K’), the P/A Nash equilibrium characterized by $q_1^c = 5\cdot(100 + 0.1\cdot K)$ and $q_2^c = 2.5\cdot(100 - 0.2\cdot K)$ exists and is the unique pure-strategy Nash equilibrium; for a line of thermal capacity between 53.6 MW and 115 MW (i.e., K’ < K < K*), no pure-strategy Nash equilibrium exists; and for a line of thermal capacity higher than 115 MW (i.e., K* < K), the unconstrained Nash-Cournot equilibrium characterized by q_1^{UCDE} = 633 MWh and q_2^{UCDE} = 333 MWh exists and is the unique pure-strategy Nash equilibrium.

Suppose that the capacity of the transmission line connecting the cheapgen and the deargen is currently 50 MW. With this transmission capacity, the cheapgen hourly produces 525 MWh of output while the deargen hourly generates 225 MWh and the market-clearing prices are $52.5/MWh at node 1 and $65/MWh at node 2, at the unique pure-strategy Nash equilibrium. Thus, at the unique equilibrium, the cheapgen earns a profit of $27,563/h and the deargen earns a profit of $10,125/h. Under these conditions, and without considering any investment cost, social welfare is equal to $56,531/h.

If the capacity of the transmission line were increased by a large-enough amount such that it became greater than K* (i.e., if the current line capacity were increased by more than 65 MW), then the transmission capacity constraint would not be binding and the firms would compete as Cournot duopolists in the combined market. As result of that, the cheapgen would earn a profit of $26,741/h and the deargen would earn a profit of $7,407/h, as previously mentioned. This would result in a reduction in profits for both generation firms as compared to the pre-expansion situation. Consequently, neither the cheapgen nor the deargen have incentive to support such an investment, although it improves social welfare (from \$56,531/h to \$65,963/h, without considering any investment cost).

On the other hand, if the thermal capacity of the transmission line were slightly increased from 50 MW to 52 MW (note that 52 MW < K'), then the cheapgen would hourly produce 526 MWh while the deargen would hourly produce 224 MWh and the market prices would be \$52.6/MWh at node 1 and \$64.8/MWh at node 2, at the unique pure-strategy Nash equilibrium. Thus, the cheapgen would earn a profit of \$27,668/h and the deargen would earn a profit of \$10,035/h. Under these conditions, and without considering any investment cost, social welfare would be \$56,554/h. Comparing the results obtained when K = 50 MW and when K = 52 MW, we verify that, as the transmission capacity increases from 50 MW to 52 MW: (i) the cheapgen increases its output at the equilibrium, (ii) the equilibrium price at node 1 increases, (iii) the cheapgen's profit increases (which confirms the cheapgen's incentives to support this transmission expansion), (iv) the deargen reduces its output at the equilibrium, (v) the equilibrium price at node 2 decreases, (vi) the deargen's profit decreases (which confirms the deargen's disincentives to support this transmission expansion), and (vii) social welfare increases. Consequently, these results verify that, while a P/A Nash equilibrium prevails, the cheapgen has incentives to support an increase in the capacity of the transmission line while the deargen has disincentives to support such an expansion. As mentioned before, this conclusion is only valid for upgrades that increase the capacity of the line up to K'. This means that if, as we assumed, the current line capacity is 50 MW, then the "positive" incentives of the cheapgen to support socially-efficient transmission investments are only guaranteed for incremental expansions smaller than 3.6 MW. Unfortunately, the lumpiness property of transmission investments makes these investments unlikely to occur in practice.

4.2 Scenario II: generation firms can hold FTRs

Now, suppose that each firm holds half of the available FTRs (i.e., $\alpha_1 = \alpha_2 = 0.5$). In this case, assuming that the current line capacity is 50 MW, the cheapgen hourly produces 537.5 MWh while the deargen hourly generates 212.5 MWh and the market-clearing prices are \$51.3/MWh at node 1 and \$67.5/MWh at node 2, at the unique Nash equilibrium. Thus, with these FTRs fractions, the cheapgen earns a profit of \$27,953/h and the deargen earns a profit of \$10,500/h. (Under these conditions, and without considering any investment cost, social welfare is \$57,227/h.) Consequently, this numerical example makes clear that, by holding some FTRs, both generation firms increase their profits with respect to the benchmark case.[16] Furthermore, by comparing the benchmark case ($\alpha_1 = \alpha_2 = 0$) and the case where $\alpha_1 = \alpha_2 = 0.5$, we conclude that, when holding FTRs, the cheapgen has incentives to increase its production (and, in this way, to decrease its nodal price) while the deargen has incentives to decrease its production (and, in this way, to increase its nodal price) in order to increase their revenues from congestion rents. From these results, we can infer that, if generation firms with local market power held FTRs, then these transmission rights would likely increase their profits.

Using a procedure similar to the one followed in the benchmark case, we can compute both the smallest transmission line capacity that can support an unconstrained Nash-Cournot duopoly equilibrium, K*, and the largest line capacity that can support a P/A Nash equilibrium, K’, for different values of α_1 and α_2. By varying the values of α_1 and α_2, it is easy to verify that both K* and K’ increase as α_1 and/or α_2 increase. For instance, with $\alpha_1 = \alpha_2 = 0.5$, we obtain K* = 127.3 MW and K’ = 88 MW, which confirms an increase in the values of K’ and K* with respect to the

[16] Recall that, when generation firms are not allowed to hold FTRs and the line capacity is 50 MW, the cheapgen optimally produces 525 MWh while the deargen optimally generates 225 MWh and the market-clearing prices are \$52.5/MWh at node 1 and \$65/MWh at node 2. Thus, in this case, the cheapgen earns a profit of \$27,563/h and the deargen earns a profit of \$10,125/h. The reader should remember that we do not consider any cost of acquiring FTRs in our calculations.

benchmark case.[17] Consequently, in this case, both generation firms will support a P/A Nash equilibrium up to a line capacity larger than the benchmark case threshold. This result suggests that, while the P/A Nash equilibrium prevails, it would be more likely that the cheapgen supports a social-welfare-improving transmission expansion when it holds FTRs than when it does not hold FTRs.

By varying the values of α_1 and α_2, it is straightforward to verify both that the larger α_1, the stronger the cheapgen's incentive to increase its production (and, in this way, to decrease its nodal price) and that the larger α_2, the stronger the deargen's incentive to reduce its production (and, in this way, to raise its nodal price). Accordingly, when the cheapgen holds all the available FTRs, the consumers located at node 1 benefit the most from the nodal price reduction while the surplus of the consumers located at node 2 remains at the benchmark's level (because the deargen has no extra incentive to reduce its production and, thus, increase its nodal price when $\alpha_2 = 0$). Consequently, the values of α_1 and α_2 that maximizes social welfare are $\alpha_1 = 1$ and $\alpha_2 = 0$.[18] From this result, we can infer that, if all FTRs were allocated or auctioned off to generation firms that are net exporters, then these firms would have the correct incentives to support social-welfare-improving transmission expansions.

5. Conclusions and Future Work

In this paper, we analyzed how the exercise of local market power by generation firms alters the firms' incentives to support social-welfare-improving transmission investments in the context

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[17] Recall that, in the benchmark case ($\alpha_1 = \alpha_2 = 0$), we have K* = 115 MW and K' = 53.6 MW.
[18] When $\alpha_1 = 1$, $\alpha_2 = 0$ and K = 50 MW, we obtain a Nash-Cournot equilibrium characterized by: q_1 = 550 MWh, q_2 = 225 MWh, P_1 = \$50/MWh, and P_2 = \$65/MWh. Thus, in this case, social welfare is $W = PS + CS = \pi_1 + \pi_2 + CS_1 + CS_2$ = \$28,250/h + \$10,125/h + \$12,500/h + \$7,563/h = \$58,438/h (without considering any investment cost). This social welfare represents an increase of 3.4% with respect to the case without FTRs (i.e., a change from W = \$56,531/h when $\alpha_1 = \alpha_2 = 0$ to W = \$58,438/h when $\alpha_1 = 1$ and $\alpha_2 = 0$).

of a two-node network. We explored how such incentives are affected by the ownership structure of FTRs and how the FTRs' allocation may be used to both align the incentives for transmission expansion of the different market participants and mitigate conflicts of interest when such expansions are socially beneficial.

Our analysis of the two-node network showed that, as long as a P/A Nash equilibrium prevails, the cheapgen has incentives to support an increase in the capacity of the transmission line while the deargen has disincentives to support such an expansion. We also showed that, when the generation firms hold FTRs, these firms will support a passive/aggressive Nash equilibrium up to a line capacity larger than the benchmark case threshold, which implies that it is more likely that the cheapgen supports a social-welfare-improving transmission expansion when it holds FTRs than when it does not hold FTRs.

We also showed that, by holding some FTRs, both generation firms could increase their profits with respect to the benchmark case. Furthermore, if all FTRs were allocated or auctioned off to generation firms that are net exporters, then these firms would have the correct incentives to support social-welfare-improving transmission expansions.

Although these conclusions were derived using a simple two-node network, we believe that they extend to more complex networks (as long as only few lines of the network are congested).

Future work will need to consider the case where the line capacity is neither too small nor too high (i.e., using the paper's notation, the case where K is such that $\text{Min}\{K', K^*\} < K < \text{Max}\{K', K^*\}$). Such analysis is complex because the existence of a pure-strategy Nash equilibrium is not guaranteed in this case.

Appendix

Consider a point of operation, (q_1^c, q_2^c), such that q_1^c is the profit-maximizing output of the cheapgen when it faces an inverse demand curve given by $P_1(q_1 - K)$, which is the cheapgen's native inverse demand shifted rightward by K, and q_2^c is the output of the deargen when it maximizes its profit given the residual inverse demand it faces, $P_2(q_2 + K)$, which is the deargen's native inverse demand shifted leftward by K. Next, we present a formal proof that (q_1^c, q_2^c) corresponds to a Nash equilibrium.

First, let's analyze the cheapgen's incentive to deviate from q_1^c. Suppose the cheapgen decreases its output by a small positive amount, ε, and the output of the deargen remains unchanged. Then, there are three possible cases: (i) q_t is unchanged and the consumption at node 1 decreases by ε, (ii) q_t decreases by ε and the consumption at node 1 does not change, and (iii) both q_t and the consumption at node 1 decrease by less than ε. In case (i), the line is still congested ($q_t = K$), but the nodal price at node 1 increases as a result of the reduction in the consumption at that node. Hence, because we assumed that q_1^c maximizes the cheapgen's profit given that $q_t = K$, this deviation could not increase the cheapgen's profit in this case. In cases (ii) and (iii), q_t decreases and, thus, the line becomes slightly decongested ($K - \varepsilon \leq q_t < K$). For a sufficiently small ε, the reduction in the consumption at node 1 (if any) would still result in $P_1(q_1 - q_t) < P_2(q_2 + q_t)$, so that the line would become congested again unless the cheapgen aggressively reduced its output (and thus its local consumption) to increase its nodal price up to the price at node 2.[19] Therefore, *decreasing its output from q_1^c* is not a profitable deviation for the cheapgen.

Now, suppose the cheapgen increases its output by a small positive amount, ε (i.e., from q_1^c to $q_1^c + \varepsilon$), and the output of the deargen remains unchanged. Then, the consumption at node 1 must

[19] Note that, without changing the deargen's output, it is not possible to equalize nodal prices at the level of the cheap node (i.e., to reduce the price at node 2 to the node-1 price level) because the consumption at node 2 can only increase by at most ε ($K - \varepsilon \leq q_t < K$), resulting in a small price reduction (for sufficient small ε). If the cheapgen aggressively reduced its output, then it would produce significantly less than q_1^c (although at a higher price) and export almost the same quantity, for a sufficiently small ε (otherwise, the cheapgen could increase q_t without changing neither its local consumption nor its nodal price, and thus increasing its profit). Hence, because we assumed that q_1^c maximizes the cheapgen's profit given that $q_t = K$, this deviation could not increase the cheapgen's profit.

increase because q_t cannot be increased further than K. If q_t did not change, then the line would still be congested, but the nodal price at node 1 would decrease (as a result of the increment in the consumption at that node). Hence, because we assumed that q_1^c maximizes the cheapgen's profit given that $q_t = K$, this deviation could not increase the cheapgen's profit in this case. If q_t decreased, then the consumption at node 1 would increase even more (and, thus, the price at node 1 would decrease even more) unless the cheapgen's output were reduced. However, because a reduction of q_t means that the line becomes decongested, nodal prices should be equal in that case (otherwise, generation firms would congest the line again). Consequently, it is not feasible for the consumption at node 1 to increase and for the line to remain decongested (as long as the output of the deargen remains unchanged). Moreover, if the cheapgen's output were reduced, then the analysis would be analogous to the previous case (where the cheapgen decreases its output by ε), which, as we already showed, would lead to an unprofitable deviation. Therefore, *increasing its output from* q_1^c is not a profitable deviation for the cheapgen.

Now, let's analyze the deargen's incentive to deviate from q_2^c. Suppose the deargen increases its output by a small positive amount, ε, and the output of the cheapgen remains unchanged. Then, there are three possible cases: (i) q_t is unchanged and the consumption at node 2 increases by ε, (ii) q_t decreases by ε and the consumption at node 2 does not change, and (iii) q_t decreases by less than ε and the consumption at node 2 increases. In case (i), the line is still congested ($q_t = K$), but the price at node 2 decreases as a result of the increment in the consumption at that node. Hence, because we assumed that q_2^c maximizes the deargen's profit given that $q_t = K$, this deviation could not increase the deargen's profit in this case. In cases (ii) and (iii), q_t decreases and, thus, the line becomes slightly decongested. For a sufficiently small ε, the increment in the consumption at node 2 (if any) would still result in $P_1(q_1 - q_t) < P_2(q_2 + q_t)$, so that the line would become congested again unless the deargen aggressively increased its output (and thus the local consumption) to reduce its nodal price up to the price level of node 1. If this aggressive output increment happened, then the deargen would produce significantly more than q_2^c and import almost the same quantity, for a sufficiently small ε (otherwise, the deargen should compensate any reduction of q_t with an increment in production to keep the same price at both nodes). Hence, because we assumed that q_2^c maximizes the deargen's profit given that $q_t = K$, this deviation could not increase the deargen's profit. Therefore, *increasing its output from* q_2^c is not a profitable deviation for the deargen.

Now, suppose the deargen decreases its output by a small positive amount, ε, and the output of the cheapgen remains unchanged. Then, the consumption at node 2 must decrease because q_t cannot be increased further than K. If q_t did not change, then the line would still be congested, but the nodal price at node 2 would increase (as a result of the reduction in the consumption at that node). Hence, because we assumed that q_2^c maximizes the deargen's profit given that $q_t = K$, this deviation could not increase the deargen's profit in this case. If q_t decreased, then the consumption at node 2 would decrease even more (and, thus, the price at node 2 would increase even more) unless the deargen's output were increased. However, because a reduction of q_t means that the line becomes decongested, nodal prices should be equal in that case. Consequently, it is not feasible for the consumption at node 2 to decrease and for the line to remain decongested (as long as the output of the cheapgen remains unchanged). Moreover, if the deargen's output were increased, then the analysis would be analogous to the previous case (where the deargen increases its output by ε), which, as we already showed, would lead to an unprofitable deviation. Therefore, *decreasing its output from* q_2^c is not a profitable deviation for the deargen. This completes the proof that (q_1^c, q_2^c) is a Nash equilibrium.

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